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Processes and Structures:
The Art and Science of Nature in *Nature*

Martin Kemp

The invitation to deliver a public lecture at the Canadian Centre for Architecture gives me a welcome opportunity to look back again over the regular column -- generally consisting of six-hundred-word pieces, each with one illustration -- that I have been writing in the science magazine *Nature*. The first two years of essays (at that point I was writing on a weekly basis) were brought together in the book *Visualizations*. Since then, there have been three years of monthly essays. It is good to be able to reflect on the years of writing, and to share with you some thoughts as to whether they are anything more than a series of separate, discrete essays. Each obviously had to stand on its own. However, are there motifs and undercurrents that can be drawn out of the diverse topics, which span a wide range of sciences, technologies, and visual arts from the Renaissance to today?

Nature, as we know, is a very distinguished periodical. Founded in 1869, it has undergone many reincarnations, signalled by the multiple redesigns of its cover -- a process that has occurred ever more frequently as design fashions and technologies have changed at an accelerating rate. As a visual historian, one of the questions I am interested in asking is why *Nature* looks like it does now, and how this look relates to its past appearances. I wrote an essay in *Visualizations* specifically on this topic. The question as to why human-made things look like they do is a fascinating and complex matter, extending beyond the field of the history of art or even of design. It is a question we can ask of anything that has been contrived by humans -- anything that is “designed” in some shape or form. And there is a special message carried by each of the resulting design solutions -- embodying what we call the style of the thing -- that can tell us a huge amounts about the processes of visualization, the intended modes of visual communication to the supposed audience, and the whole aura of the enterprise in which the content or subject (science in the case of *Nature*) and the form or vehicle (the weekly journal in this case) are complicit. For instance, no science magazine could now present itself seriously without openly brandishing a high-tech air on its cover.

In the introduction to the book of the essays, I used the term *structural intuitions* as a way of trying to capture what I felt about the way in which visuals arts and sciences relate -- at least as I am primarily interested in that problem. I am not so much interested in *influence* (however defined). Obviously science can be said to exercise an influence upon art, artists, and architects, and in particular instances art production and architecture have an influence on science. But to chart influence seems to me to be a less interesting question than to tunnel underneath the surface to ask: Are there shared intuitions at work? Is there anything that creators of artefacts and scientists share in their impulses, in their curiosity, in their desire to make communicative and functional images of what they see and strive to understand? Before attempting to show where three answers to these questions might lie, I should make a necessary qualification. Such is the variety in the practices in the "art world" and in "the sciences" that it is parlous to make overarching generalizations about all "artists (including architects)" and all "scientists." I will be talking about something that I believe to be widespread and fundamental, but not uniform or universal across all of those pursuits we call arts and sciences.

It should also be said, in the present context, that structural intuitions have particular applicability to engineering solutions in architecture. An instinctive and often somatic sense of what might be stable and strong is obviously central to the processes of architectural design, particularly at the conceptual stage of projects that push at the boundaries of existing solutions.

I felt that the term structural intuitions served in one phrase to capture what I was trying to say, namely that painters, sculptors, architects, engineers, designers, and scientists often share a deep involvement with the beguiling structures apparent in the configurations and processes of nature -- both complex and simple. Looking at nature, we rely heavily on an inbuilt sense that there is some kind of order or underlying structures "out there." I think we gain a deep satisfaction from the perception of order within apparent chaos, a satisfaction that depends on the way that our brains have evolved mechanisms for the intuitive extraction of the underlying patterns, static and dynamic. There is a delicious interplay between the structures we have in here -- in our brains -- and the structures out there -- not just static structures but also temporal processes. I am interested in that interplay, and in how many creative makers of things and scientists are involved in essentially parallel businesses when they develop their intuitions into their final products. How designers and scientists explore the interplay, how they develop their understanding, and how they embody their "results" in their creations, are obviously very different, particularly in terms of the vehicles they use and the institutional contexts within which they operate. But I think that there is often a shared itch of looking at something in a spirit of wonder, and then saying: I really want to know what that is about -- whether it is a flame leaping in a fire, water moving in a river, a tree branching, the spiral of a shell, the grandest motion of the heavens or tiniest scatter of atomic particles. Many scientists start with a fundamental feeling that there is a pattern, that there is something wonderful, fascinating, awesome in what lies behind the observed phenomena. Many designers of things start at fundamentally the same point. I think they are both starting with intuitions about processes and structures, about order and disorder.

To give a concrete example of what I mean by structural intuitions, let me take what was one of the most surprising and delightful episodes in the whole of my writing in *Nature*.

I wrote about a youngish British artist who -- amongst other things -- has made dust landscapes. These landscapes are made by taking a large steel plate, into which holes are drilled at irregular intervals. A layer of cement dust is sieved evenly onto the plate. Obviously, some powder drops through the holes. The result is a wondrous landscape of mountains and cellular valleys, linked by hyperbolic ridges. Some of his dustscapes have filled whole rooms, and are infinitely varied and complex, yet somehow unified and harmonious.

When I first saw a small-scale model of the landscapes, I said to him: "This reminds me of the theory of self-organized criticality [a relatively new idea at that time], which is exemplified in the model of a sand pile." If sand grains are dropped continuously from a fixed point, they will accumulate as a conical pile, but, as we are likely to know from childhood games on sandy beaches, the sides of the pile tend to collapse as their angle becomes steeper. Avalanches suddenly occur. We know from complexity theory that the occurrence of the avalanches is unpredictable but not random. There are probabilities at work, and limiting parameters on the steepness of the slope, but the point in time when the pile collapses and turns into a different cone is not precisely predictable, nor is the precise post-avalanche shape.

Jonathan Callan did not know about self-organized criticality, and there is no reason why he should have done. I was not trying to prove whether he studied science or not, but I wanted to suggest that he had exploited his own kind of artist's sense of something fascinating in the shapes and patterns that emerged from his process. I suggested to him that the configuration should be photographed directly from above as well as from a lateral view, because I was very interested in the cellular structure that had emerged. If you look his dustscapes from a "bird's eye" view, they present a pattern of cells, separated by cell walls. When the article was published in *Nature*, Adrian Webster, from the Royal Observatory in Edinburgh, wrote to the journal explaining that the configuration was that of Voronoi cells, named after Georgii Voronoi, a Russian mathematician working at the turn of the nineteenth to the twentieth century. Voronoi cells can be created as follows. A series of point vacuums are distributed irregularly across a plane. Each mobile particle on the plane will cascade towards the vacuum closest to it. If we draw the boundaries that decree in which direction a given particle will move, we find that they form irregular polyhedra around the "nuclei" of the vacuums. The whole array is called a Voronoi tessellation. Webster also pointed out that one of the possible models for the organization of galaxies is a "Voronoi sponge," a three-dimensional version of this flat system, and that the galaxies might be arranged along the cell walls. The appearance of this model is a kind of cosmic foam. But this was not the end of the story. Ian Stewart subsequently picked up the theme of Callan and Voronoi cells in his column on "Mathematical Recreations" in *Scientific American*. From their artistic beginnings, Jonathan Callan's little bits of dust underwent a remarkable galactic voyage.

The way that the whole discussion developed was unexpected and thrilling for me. The process of creating a work of art through a physical process had tapped into basic patterns of organization, ranging from tiny cellular structures to the largest configurations that we can envisage. Something that emerged, very delightfully, is that the artistic and mathematical intuitions are not dependent on scale; that is to say, they potentially apply not only to the smallest systems we can discern but also to the very largest we can conceive, embracing all the intermediate steps.

Susan Derges, about whom I have also written in the *Nature* series, is looking at comparable phenomena in her art. She regularly uses the technique of photograms, photographic prints made directly from nature without a camera. She works in Devon and has made a series of works on the flow of water in the River Taw over the seasons. At nighttime, underneath the surface of the flowing water -- or in the winter under the skin of ice -- she placed large slides containing photographic paper. They were about two meters high and one and a half meters across, dimensions comparable to the human body. She then fired a flashlight above the water, recording the "fingerprint" of the wave patterns in the water currents at that particular moment. Her photograms also recorded the shadows from overhanging branches. The results are uncannily like Japanese screens and it is no surprise to find that Derges has resided in Japan and is very involved with Japanese art.

The patterns that she picked up are of considerable interest to specialists in fluid dynamics, including "standing waves," which are more or less stationary with respect to the banks. If you look into the detail, you can see dynamic patterns emerging from the apparent chaos of flowing water. We can sense an internal structure that is cellular in nature, like a magnified photograph of the human skin or other living tissue. Not only do we have a sense that the structures inherent in processes are valid across different scales, but that they also operate across different materials, solid and fluid. Susan Derges is very concerned with insights drawn from science and is well read in the sciences of complexity -- chaos theory, fractals, and so on -- but she is not literally making works on scientific themes in an illustrative manner. She is not "influenced" by chaos theory, in a literal sense, but rather draws it into her ever-expanding field of intuition and understanding.

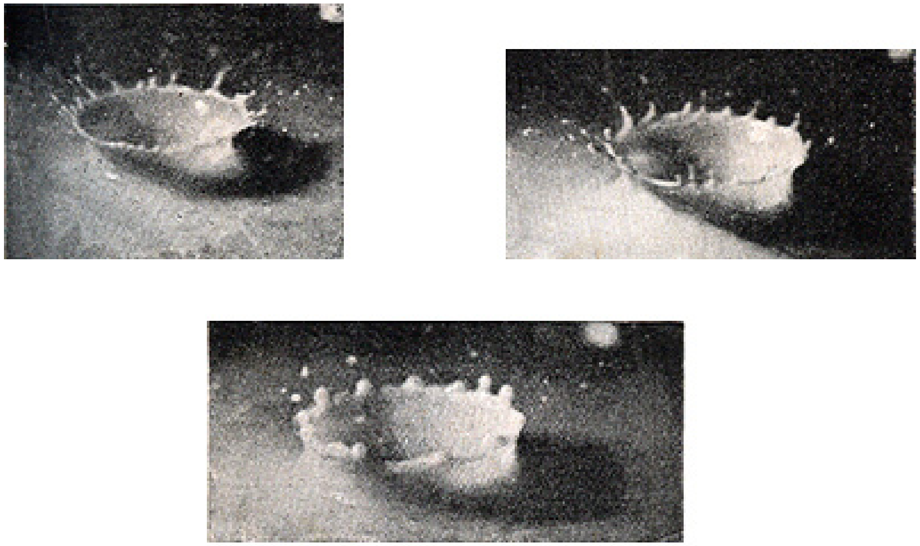
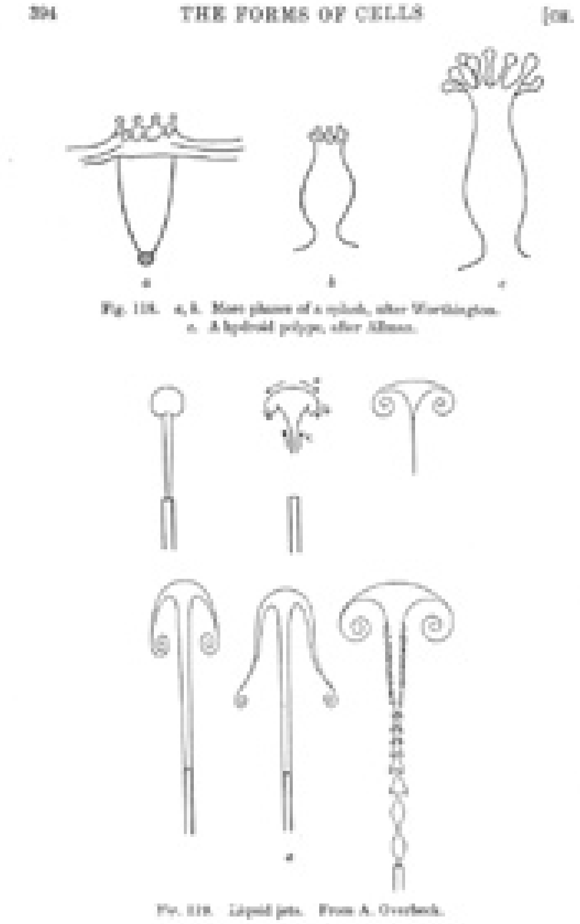


Fig. 70. Phases of a Splash. (From Worthington.)

Fig. 1 Arthur Worthington: photographs showing the phases of a milk splash, 1908, as reproduced in D'Arcy Wentworth Thompson, *On Growth and Form*, Cambridge, 1917, 235, Blacker-Wood Library of Biology, McGill University, Montreal, photo © Megan Spriggs 2005



394 THE FORMS OF CELLS [CH.

Fig. 2 Diagrams of the forms of cells, from D'Arcy Wentworth Thompson, *On Growth and Form*, 2nd ed., Cambridge and New York, 1942, 394, Blacker-Wood Library of Biology, McGill University, Montreal, image © Megan Spriggs 2005

Many of the ways in which we have learnt to "see" natural phenomena since the nineteenth century have involved instruments to extend the capacities of our visual faculty. Photography is integral to these new modes of vision. Instantaneous or split-second photography is an important case in point. A notable early example is the series of remarkable photographs of splashes taken by Arthur Worthington and published in 1908 (Fig. 1). The beautiful corona thrown up by a ball dropping into a bowl of milk has become an iconic image, not least through the later entrepreneurial efforts of Harold Edgerton at MIT's "Strobe Alley." The image has developed a life of its own. For example, milk delivery tankers in the southeast of England are adorned with a rather literal version of the "Edgerton splash." It has become the *Mona Lisa* of fluid dynamics, just as DNA has become the *Mona Lisa* of the biological sciences.

Worthington's photographs were seized on by D'Arcy Thompson, the great Scottish biologist and classical scholar, who wrote an extraordinary book on natural morphologies, which has served as an enduring source of inspiration for artists, architects, and particularly engineers, since it was published in 1917. The book, *On Growth and Form*, is one of the greatest works of scientific literature (Fig. 2). In a very beautiful passage, Thompson writes of a thrown pot as a stilled splash.

> To one who has watched the potter at his wheel, it is plain that the potter's thumb, like the glass-blower's blast of air, depends for its efficacy upon the physical properties of the medium in which it operates, which for the time being is essential a fluid. The cup and the saucer, like the tube and the bulb display (in their simple and primitive forms) beautiful surfaces of equilibrium as manifested under certain limiting conditions. They are neither more nor less than glorified "splashes," formed slowly under conditions of restraint which enhance or reveal their mathematical symmetry.

This is a beautiful insight. Looking at Worthington's corona, he could see that it rhymed with many other forms and phenomena, including the semi-liquid clay rising under the shaping caress of the potter's hand. He also looked, as we will see, to analogous forms in polyps and medusoids. What Thompson is doing here corresponds precisely to what I am calling structural intuitions. What I am trying to capture with this phrase is the age-old way that scientists, like artists, want to see inside the structure

Fig. 3 Leonardo da Vinci: drawing of a seated figure and studies of water in movement (Royal Library, Windsor) from *The Notebooks of Leonardo da Vinci*, ed. and trans. Edward MacCurdy, London, 1938, vol. II, opposite p. 105, Call. no. CAGE W7606, Collection Centre Canadien d'Architecture / Canadian Centre for Architecture, Montréal

Fig. 4 Leonardo da Vinci: studies of a woman's head and coiffure, ca 1504–06, for Leda (Royal Library, Windsor) from *The Notebooks of Leonardo da Vinci*, ed. and trans. Edward MacCurdy, London, 1938, vol. II, opposite p. 284, Call no. CAGE W7606, Collection Centre Canadien d'Architecture/Canadian Centre for Architecture, Montréal

of seen phenomena, extracting orders of varying complexity from the apparent chaos of appearance. No one was more consistent in this respect than Leonardo da Vinci.

Leonardo was continually asking about the structures, static and dynamic. All his remarkable depictions of forms and phenomena represent acts of structured demonstration rather than "simple" or direct recording. His water drawings, for example, are replete with ideas about how water *should* work according to the laws of dynamics as conceived in the Aristotelian tradition (Fig. 3). They are very much constructed images, in which it is impossible to separate observation and representation from analysis and synthesis. Leonardo, like Dürer, never looked at anything without asking questions about the nature of the seen phenomenon. The art of drawing for Leonardo as for Dürer -- albeit in distinctively individual ways -- is an art of understanding. They are neither artists nor scientists, in that our pedestrian terminology simply fails to capture what they did in blending the deepest intellectual insight into the operations of nature with the highest imaginative acts of re-making.

One of the most characteristic motifs in Leonardo's thought involves visual analogy. Looking at water flowing turbulently, he writes:

> Observe the motion of the surface of water, which resembles the behaviour of hair, which has two motions, of which one depends on the weight of the strands, the other on the line of its revolving; thus water makes revolving eddies, one part of which depends on the impetus of the principle current, and the other depends on the incident and reflected motions.

He is thus breaking down phenomena in statics and dynamics into two vectors to satisfy intellectually his intuitive sense that one thing reminds him of another. Accordingly, when he designs a wig for Leda in his painting of *Leda and the Swan*, his artificial structure exploits these insights. His artificial elaboration of the natural motif is set in telling counterpoint to Leda's natural hair as it spouts impetuously from apertures at the centre of the lateral whorls in her wig (Fig. 4).

Leonardo's indelible sense that processes and structures were locked together in patterns definable according to mathematical rule is nicely manifested in his vision of fluid flow through tubes or channels. Whether the system of flow involved water in rivers, sap in a tree, or the bronchi of lungs, he argued that the same *ragione* applied. The volume of fluid passing within a tube is understood by Leonardo as proportional to the cross-sectional area of the tube. Thus at each level in a branching array the total cross-sectional area should remain constant for efficient flow. The designer of canals who wished to achieve non-turbulent flow in a branching system should learn the necessary lesson from nature's branching systems.

Thompson proceeded very much along the same lines. He looked, for instance, at the way in which viscous substances dropped into thinner media produce wonderful branching shapes, which resemble the forms of gelatinous marine organisms such as medusoids. In a nice instance from modern ceramics, the artist Joan Lederman has been using mud millions of years old, excavated deep in the sea bed by oceanographic surveyors, to glaze thrown pots (Thompson's splashes). She discovered that the muds, rich in foraminifera skeletons from ancient eras, spontaneously adopt dendritic formations during the course of firing -- a set of splashes within a splash, as it were.

In a related structural realm, Thompson also delighted in the elegant experiments on soap films performed by Plateau, the Belgian physicist, in which wire frames were used to set up "membranes" in a variety of geometrical configurations. Thompson was drawn to the evident parallels with some marine micro-organisms, most notably the skeletons of the radiolaria illustrated in Ernst Haeckel's beautifully illustrated book *Radiolarien* in 1862 (Fig. 5). Studying the comparable configurations disclosed by Plateau and Haeckel, Thompson was, like Leonardo, stimulated to ask some basic questions. Does the inorganic engineering of soap films in relation to the frames in which they are suspended tell us something fundamental about the way in which certain living things organize their structures in nature? Or, more broadly, is there such a thing as "natural engineering" that explains analogous configurations in animate and non-animate worlds in the context of physico-chemical laws? Or, in modern terms, are there common principles of spontaneous self-organization at work across the inorganic and organic worlds?

The problem for Thompson was that it was not clear what the observed analogies actually proved, suggestive though they might be. There was a

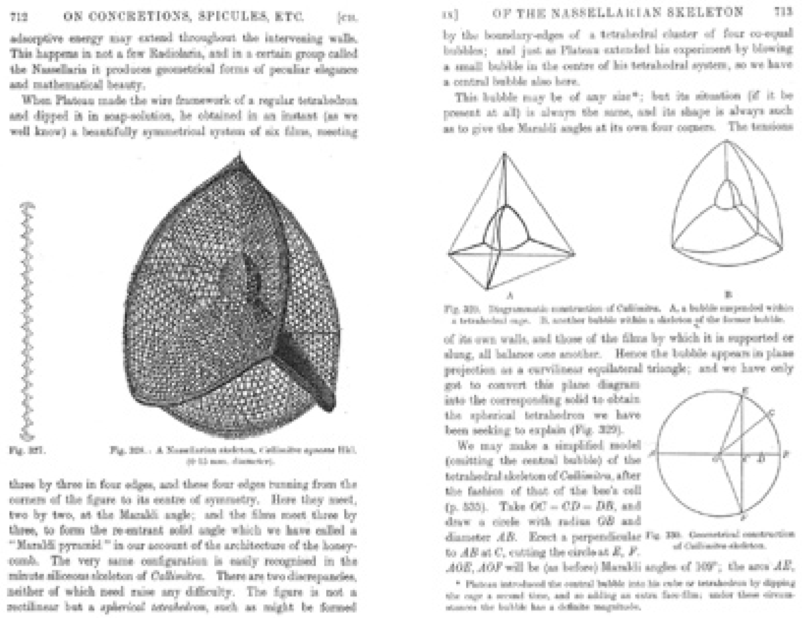


Fig. 5 Diagrams of Callimatra skeletons, after Haeckel's *Die Radiolarien*, from D'Arcy Wentworth Thompson, *On Growth and Form*, 2nd ed., Cambridge and New York, 1942, 712-713, Blacker-Wood Library of Biology, McGill University, Montreal, image © Megan Spriggs 2005

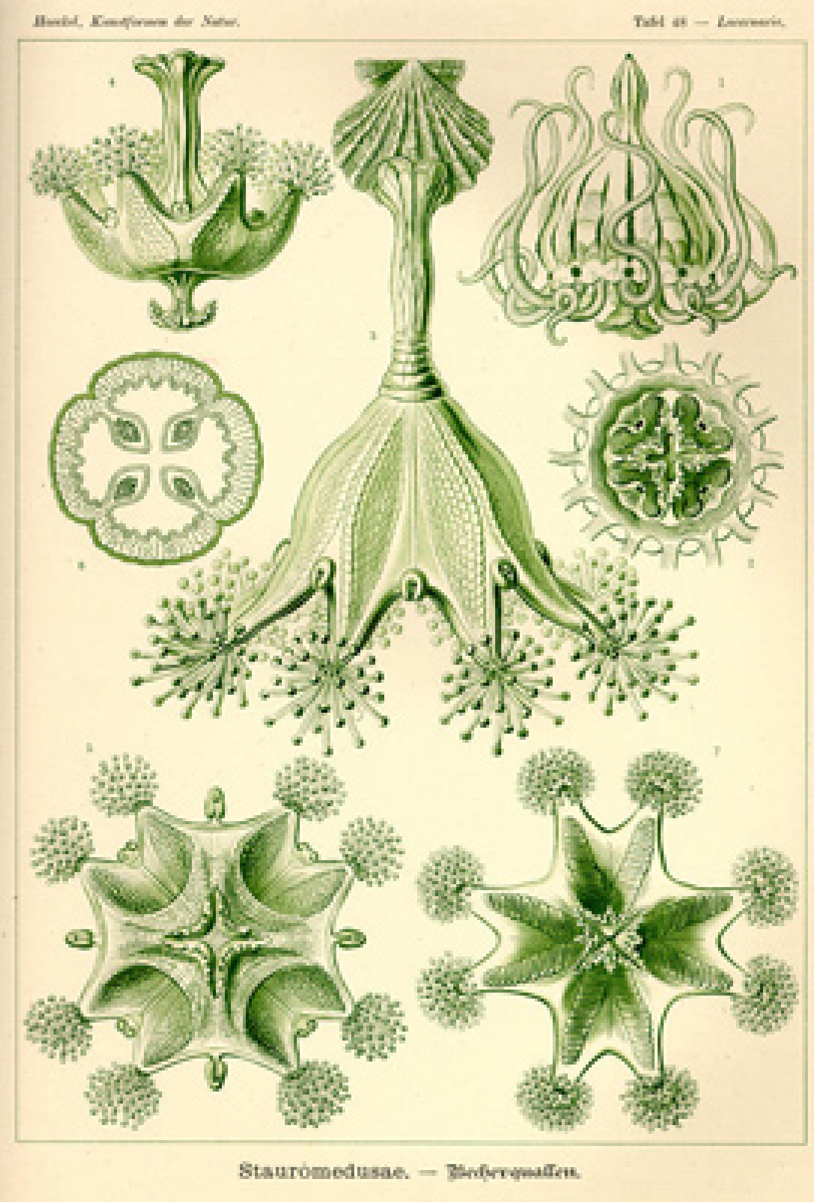


Fig. 6 Ernst Haeckel: Lucernaria, from *Kunstformen der Natur*, Leipzig and Vienna, 1899–1904, pl. 48, Institut für allgemeine Botanik, Hamburg, photo © Kurt Stüber, Max Planck Society for the Advancement of Science, 1999

sense that he was producing "so-what?" science, in which the observations could not be related to any kind of causal explanation. Now, with the advent of modern methods of computer modelling, it is possible to program in the physical parameters of the processes that shape a viscous drop and a medusoid to see what physical forces are at work in the self-organization of such analogous morphologies -- and similarly with the radiolarian frames and films, with phyllotaxis in plants, and with other self-organizing processes that Thompson looked at.

The immediate future of Thompson's insights lay as much with artists and architects as with biologists. By the 1940s and 1950s, painters, sculptors, architects, designers, and engineers were consuming Thompson's *On Growth and Form* more avidly than biologists. Mies van der Rohe was a great fan, as the 2001 *Mies in America* CCA exhibition catalogue, edited by Phyllis Lambert, makes clear. A very good example of how Thompson served artists is provided by the Russian émigré sculptor Naum Gabo, working in St. Ives, who was introduced to Thompson's work by Hubert Read, the art critic, and by Wilhemina Barns-Graham, a Scottish artist in St. Ives who had encountered the redoubtable Thompson in St. Andrews. Gabo uses a repertoire of quasi-natural forms under tension and compression, very comparable to those analyzed by Thompson. Gabo is not copying Haeckel. Nor is he copying Thompson. But the principles of the engineering of the object are understood via Thompson and the examples he illustrated in *On Growth and Form*, such as the Plateau soap bubbles. Gabo himself was trained as an engineer, and I think it shows.

I think it is generally true that people who can exercise a choice of career tend to enter particular professions precisely because they have an instinctive feeling for the forms and processes of the things at the heart of that profession. It is no coincidence that Gabo was an engineer before he became a constructivist sculptor. His own structural intuitions were naturally strong in those related fields, involving a kind of somatic engagement with the structural integrity of three-dimensional forms in geometrical configurations. It is notable that a number of the scientists we will later be encountering showed an early interest in design, in graphics, and in three-dimensional modelling.

Equally, we find that important engineer-architects exhibit a strong reaction to the engineering of biological forms in nature. The example

I am choosing is Antonio Gaudí, architect of the Sagrada Familia, the extraordinary Catalan church on which he began work in 1883 and which is still under construction. Looking at the display in Barcelona devoted to his work on the great basilica, I was fascinated but not surprised to learn that he knew the works of Ernst Haeckel. He was immensely interested in Haeckel's images of natural engineering in *Kunstformen und Natur* (1899--1904), which the German biologist had published specifically with artists and designers in mind, having found that they were already looking avidly at his illustrations (Fig. 6).

The structural principles on which Gaudí worked may be described as natural engineering, understood through an experimental method. This is exemplified in the method he adopted to design an arch-form in which all the lateral forces are resolved within the substance of the arch. A semicircular arch does not exhibit this property, and pointed gothic arches can be designed to achieve this end only to an incomplete degree. He saw that the solution is to adopt a catenary curve. This is the curve that results if we loosely suspend a chain (a catena) in a loop, hanging from its two ends. All the forces must necessarily be resolved within that curve. So Gaudí said in effect, why don't I design the arches and vaulting patterns using upside-down, hanging models? In order to study the loading on the arches, why don't I hang weights from the corresponding points on the upside-down arch? And if I then reinvert the whole thing, retaining the configuration of the catenary curves that have resulted from the resolution of the forces, I will have a structure that is wholly resolved and stable. This is an extraordinary act of intuitive brilliance on Gaudí's part, literally a vaulting insight. The kind of structural intuition involved is simultaneously physical and visual. The results have that sense of harmonic rightness that we can all feel -- the kind of inevitable rightness that characterizes all great design.

More recently, the great Swiss engineer of thin shell structures, Heinz Isler, has adopted Gaudí's inversion method to rework the principles of vault design. A frozen membrane, suspended from its corners, settles into a complex set of compound curves, serving as a template for a square vault springing upwards from four points. The breathtaking result of these kinds of structural explorations can be seen in the Brugg swimming pool by Gross and Meier, on which Isler served as the engineer. The way we often use the term "breathtaking" to describe such feats of engineering suggests that there is a bodily aspect to our response, as if

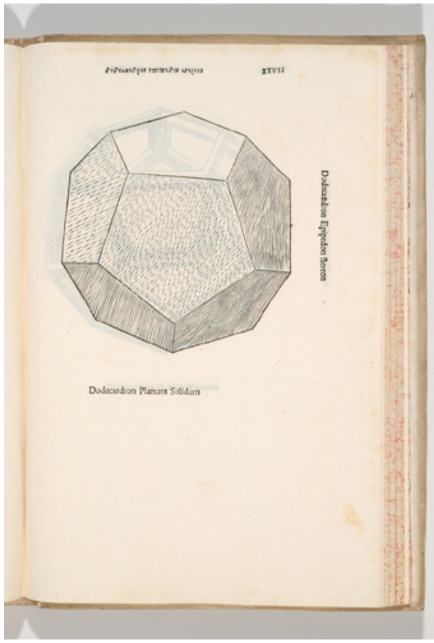


Fig. 7 After Leonardo da Vinci: woodcut showing the dodecahedron as a solid form, from Luca Pacioli, *Diuina Proportione*, Venice, 1509, pl. XXVII, Call no. CAGE W10310, Collection Centre Canadien d'Architecture/Canadian Centre for Architecture, Montréal

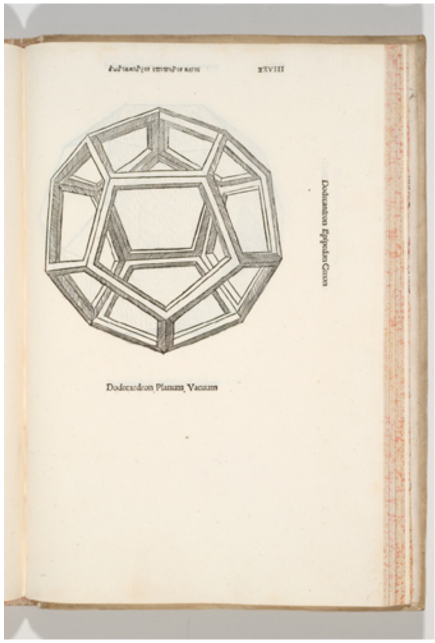


Fig. 8 After Leonardo da Vinci: woodcut showing the dodecahedron as an open frame, from Luca Pacioli, *Diuina Proportione*, Venice, 1509, pl. XXVIII, Call no. CAGE W10310, Collection Centre Canadien d'Architecture/Canadian Centre for Architecture, Montréal

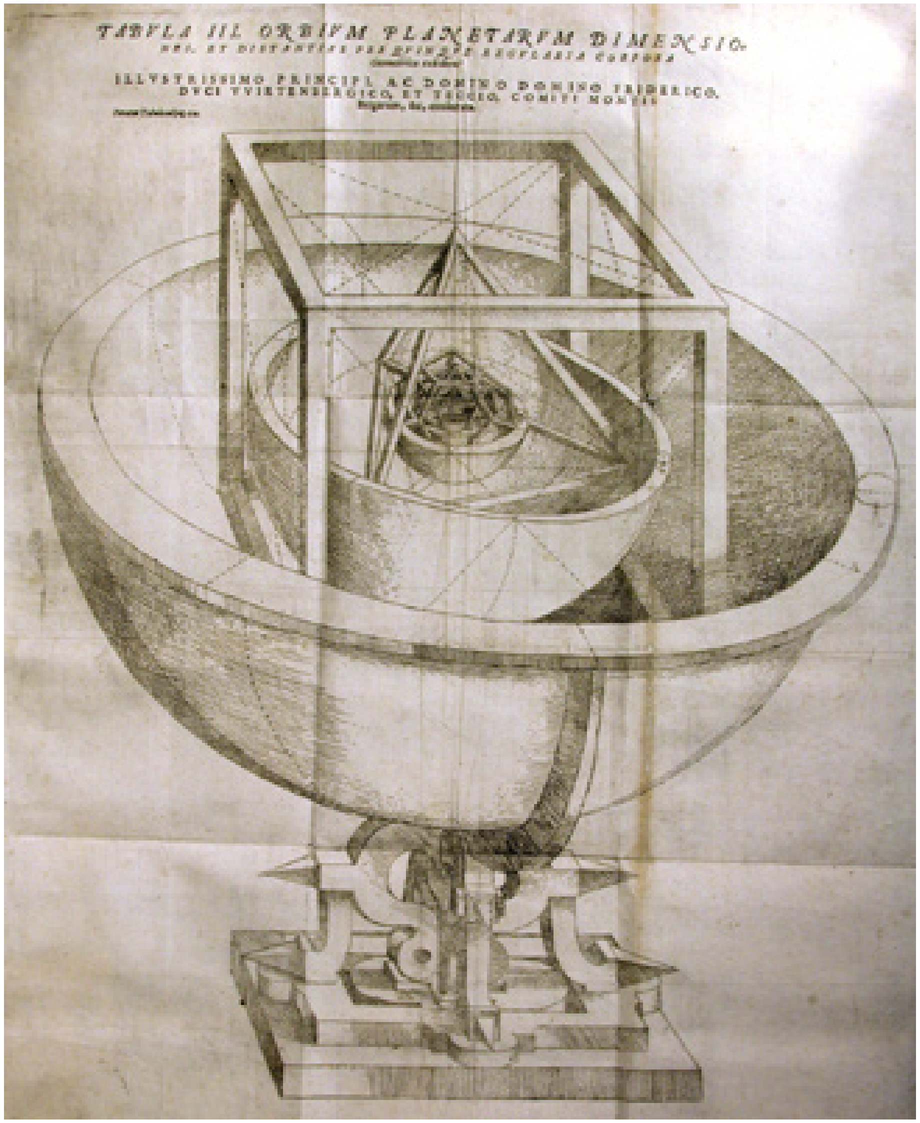


Fig. 9 Johannes Kepler: model of the cosmos, from *Mysterivm Cosmographicvm*, Tübingen, 1596, pl. III, image © History of Science Collections, University of Oklahoma Libraries

we are ourselves drawn into instinctive states of empathetic tension and compression, mirroring that of the structure itself.

One of the recurrent concerns of those drawn to these kinds of natural engineering has been the magic of the five regular polyhedra, the so-called Platonic solids. For Plato himself, the five regular bodies were identified with the four earthly elements and the cosmos, thus corresponding to a profound level of reality in the underlying organization of all things. Leonardo, while not accepting the Platonic doctrine in its literal form, was very much in tune with the idea that the perfect geometry of the solids spoke of deep truths in natural design. He was particularly fascinated by the way in which it is possible to work beguiling, semi-regular variations by truncating them (slicing off their corners) and by stellating them (building up pyramids on their faces). His most sustained engagement with the geometry of the solids came when he provided the illustrations for Luca Pacioli's *De Divina Proportione* (Figs. 7 & 8). The mathematician arrived in Milan in 1496, under the patronage of the Duke Ludovico Sforza, and the manuscript was completed two years later. Leonardo invented a brilliant method of showing the bodies both in solid form, modelled like pieces of sculpture, and in skeletal form, so that their complete spatial configuration could be more readily seen. When the illustrations were printed in 1509, they became the only Leonardo images published in his own lifetime. His own independent sketches of variations on the solids testify that Leonardo was one of those remarkable people who possess such extraordinary powers of spatial visualization that they can undertake complex manipulations of geometrical sculpture in their minds.

It was exactly this ability that served Johannes Kepler so well in his conception of the cosmos, in which the orbits of the planets are envisaged in terms as a series of nested spheres within which are inscribed the Platonic solids. This scheme was expounded and brilliantly illustrated in his *Mysterium Cosmographicum* (Fig. 9)-- a wonderful title for a book. His later treatise on world harmony abandoned this system, but the later revision does not alter the brilliance of the three-dimensional insight into the possible organization of the cosmic system. Kepler was also concerned with the search for such "Platonic forms" in the new device of the microscope, and wrote a witty treatise on the six-cornered snowflake. Again, we are encountering shared insights at scales from the very tiny to the biggest then known, courtesy of the lens-based devices of microscopes

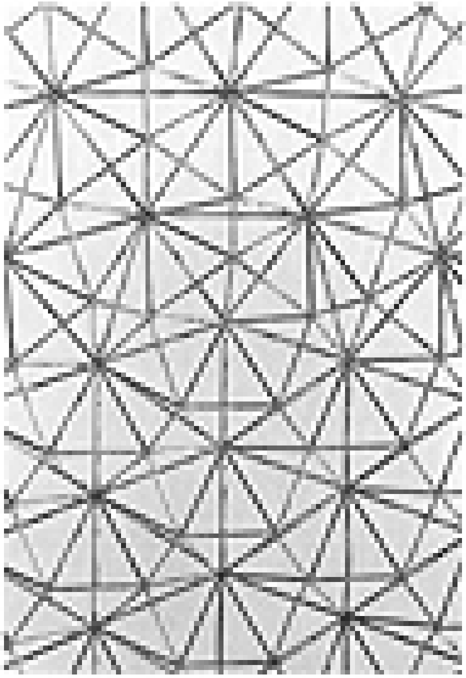


Fig. 10 Robert Duchesnay, detail of the Buckminster Fuller United States pavilion for Expo 67, 1985, Collection Centre Canadien d'Architecture/Canadian Centre for Architecture, Montréal, © Robert Duchesnay

and telescopes. It was with obvious instinctive and intellectual delight that Kepler greeted the shared structures that were emerging at extreme scales.

As the microscopists began to look through their ever-improving instruments, they encountered a wonderful world of micro-engineering. Nanotechnology is its modern equivalent. In Robert Hook's classic *Micrographia*, published in 1665, there is a wonderful description of the perceptual delights and complexities presented by the eye of a fly. He explores how varied it looks in different lights and from various orientations, and is entirely honest about how difficult it is to make sense of a complex visual array in an entirely new realm of viewing. The array of polyhedra in the compound eye was at least as wondrous as any piece of natural engineering seen with our own naked eye.

It may seem a great leap to turn from this seventeenth-century masterpiece of microscopy to the work of one of the most innovative engineer-designers of the twentieth century, Buckminster Fuller. But in terms of structural intuitions, I would like to suggest that it is but a small step. For a historian, I suppose that this kind of move could be seen as irresponsible, and it undoubtedly carries a high element of risk, inasmuch as the images are taken out of context. We are in of danger of eliding things that belong to different cultures with deeply different motivations. It is perhaps somewhat indecent for a historian to do this. But a bit of indecency is rather exciting and potentially creative. The greatest of all the structures actually built by Fuller was the geodesic dome for the American pavilion at Expo 67 in Montreal (Fig. 10). If he did not know Hooke's eye of a fly he should have done! The dome and the eye both exist in the realm of optimum design solutions, and have that sense of perfect inevitability that characterizes the most resolved acts of engineering. In that respect, I think their shared properties relate to enduring aspects in our human perception and creation of structure -- transcending time and place.

The continued vitality of this kind of design in architecture is amply demonstrated by two examples. The first is the recently-completed lattice structure of the roof of the Great Court at the British Museum, designed by Norman Foster and engineered by Buro Happold. The creative role of the engineer is crucial in determining the complex geometry of the donut-like form of the roof, which bridges the space between the circular

Fig. 11 Pierre Granche, sculptor, with Janos Baracs, engineer, *Système*, 1982, Namur Métro station, Montreal, photo © Megan Spriggs 2005

reading room and the irregular rectangle of the courtyard. It is not coincidental that much of the design philosophy of the engineering firm was set by someone who was a huge fan of D'Arcy Thompson, namely the late Sir Edmund (Ted) Happold. Throughout his work, Happold conducted a keen and fruitful dialogue between natural and human design -- an enthusiasm fully shared by Norman Foster -- and the roof of the Great Court accordingly resonates in a creative way with a series of structural skeletons in natural organisms.

The second case involves plate structures, forms composed of sets of geometric plates that are inherently stable. A natural instance of such a structure is the shell of a sea urchin. An important theorist and designer of plate structures is Janos Baracs, a Hungarian engineer in Montreal who was involved directly with the mathematicians Henry Crapo and Walter Whiteley. Baracs's ideas are spectacularly realized in the open structure of dodecahedra conceived with the artist Pierre Granche in the Namur Metro station, which excitingly assumes a clustered variation on the Leonardesque theme, hanging vertiginously above passengers ascending to and descending from the foyer of the station (Fig. 11).

That scientists have been equally alert to these kinds of structural engineering in nature can be demonstrated by two very contrasting but visually-related discoveries. The first concerns virus structures, and the second the spatial configuration of carbon sixty (C^{60}).

In the 1950s and the early 1960s new staining techniques, termed negative staining, were beginning to provide a vision of what viruses look like when viewed in an electron microscope. And very thrilling were the forms that were being discerned. These menacing little mechanisms proved to exhibit an extraordinary kind of Platonic beauty, in ironic contrast to their threat to our health. But the pictures at this early stage were unclear. In their 1960 paper on the herpes virus, Peter Wildy, William Russell, and Robert Horne grappled with how they might extract a definite structure from the somewhat unresolved images in their electron microscope. Russell explained to me how they worked out the structure of the capsomeres, which lie immediately inside the outer coating. They began to think of the ways that polygonal forms can be combined in regular and semi-regular geometrical bodies. They had to find some way of combining pentagons and hexagons together in a unified, compressed, stable structure. Two of the pioneers of virus structure, Donald Caspar and Aaron Klug, specifically cited Buckminster Fuller's studies of variations on the Archimedean solids and looked to his geodesic domes as providing design tools for modelling the viruses. When the team of Wildy, Russell, and Horne, working in Glasgow put together their first improvisatory models, made impermanently in cardboard, they had these kinds of configurations and geometrical engineering in mind.

The second story involves the discovery of C^{60}. The simpler, known forms of carbon are arranged in sheets in a lattice structure that is essentially planar. But radically new empirical evidence showed that there was a form of carbon that consisted of sixty spatially disposed atoms. This immediately posed the tricky problem of how the sixty units might be disposed in a stable array. The team working on the structure at Rice University was led towards a solution by Harry Kroto, an English scientist who was working in Texas at that time. He had earlier been to Expo 67 in Montreal, where he realized that the star structure was the American Pavilion constructed as a geodesic dome by Fuller. He had been interested as an artistically inclined young man in training as a designer, and has retained a natural flair for thinking about plastic configurations. It was he who provided a key impetus in the quest to put hexagons and pentagons together in the structure they called the "Buckminsterfullerene." The whole class of related carbon structures subsequently discovered are generically known as "fullerenes," and the structures that resemble a certain kind of panelled soccer ball were nicknamed "buckyballs." We might say that the designers of soccer balls had their own kind of structural intuition!

I am not so much talking about the *influence* of Buckminster Fuller, as defined in the conventional way, but the fact that he was an active player in the field of inspiration and lateral thinking about geometrical structures -- someone with whom creative scientists, technologists, architects, and artists regularly enter into fruitful dialogue. The reason why the Buckminster Fuller domes became relevant to virus modellers and molecular chemists is because they entertained shared intuitions that the structural factors that make a geodesic dome stable are essentially similar to those operating in the forms in nature they were investigating.

What is implicit in what I have been saying is that we are dealing not just with structures "out there," but also with structures that are integral

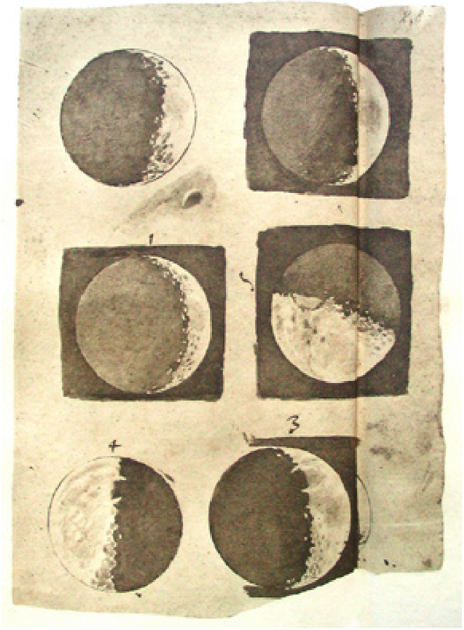


Fig. 12 Galileo Galilei: watercolour drawings of light and shade on the moon from the manuscript of *Sidereus Nuncius*, 1610 (Biblioteca Nazionale Centrale di Firenze, Galileano 48), facsimile in *Le Opere di Galileo Galilei*, vol. III, pt. 1, Florence, 1892, pl. 48, McLennan-Redpath Humanities and Social Sciences Library, McGill University, Montreal, photo © Megan Spriggs 2005

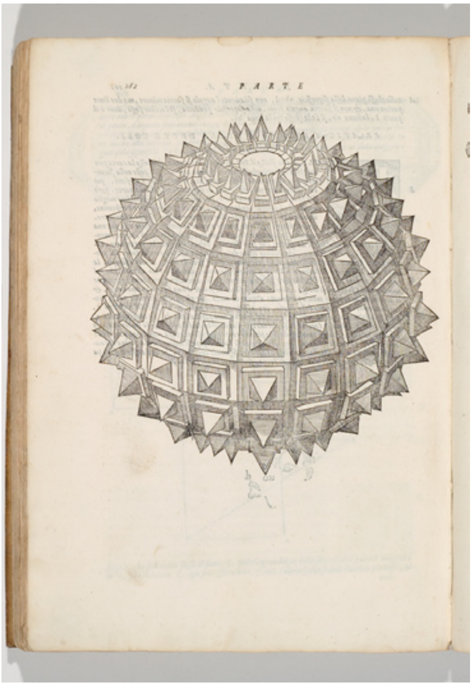


Fig. 13 Daniele Barbaro: view of a complex geometrical body in perspective from *La pratica della Perspettiva*, Venice, 1568, p. 162, Call no. CAGE W373, Collection Centre Canadien d'Architecture/Canadian Centre for Architecture, Montréal

Fig. 14 Back of hand and shrivelled apple. To illustrate the origin of certain mountain ranges by shrinkage of the globe. From James Nasmyth and James Carpenter, *The Moon: Considered as a Planet, a World, and a Satellite*, London, 1874, pl. II, McLennan-Redpath Humanities and Social Sciences Library, McGill University, Montreal, photo © Megan Spriggs 2005

Fig. 15 Topographical photograph of the full moon from James Nasmyth and James Carpenter, *The Moon: Considered as a Planet, a World, and a Satellite*, London, 1874, pl. III, McLennan-Redpath Humanities and Social Sciences Library, McGill University, Montreal, photo © Megan Spriggs 2005

to our perception of nature. We necessarily structure our seeing. Our acts of seeing coherently amidst the teeming visual array that presents itself to our eyes necessitate powerful filtering in every instance. In this case, the objects of scrutiny are filtered to draw out certain aspects of geometrical order.

One of the most famous of all acts of structured seeing was performed by Galileo Galilei in the early years of the seventeenth century, as he looked through his telescope at the moon. It was a poor quality telescope by our standards. Galileo had worked to improve the lenses significantly, but compared with modern telescopes it was quite a rough device. What he was able to see was that the surface of the moon featured what could only be -- to his eyes -- mountains and valleys. He noted that as the sun moved, little specks of light, corresponding to mountain summits, began to appear in the fringes of the shadow and gradually merged with the edge of the lit portion as the light falling on the mountains moved higher over the lunar horizon. It seems obvious to us what the explanation is, but it is only obvious once you have "seen" it, once your vision has been structurally conditioned to grasp it in this way. Other observers at the time could not "get it." They could not snap their perception into that plastic act of visualization. One reason why Galileo "got it" was that he was a very accomplished draftsman and hard learnt about the changing patterns of light and shade on solid bodies. His watercolour drawings of the changing appearance of light and shade on the moon testify to his perceptual and manual skills (Fig. 12). The act of drawing, as with Dürer and Leonardo, is an act of analysis. Galileo also knew in some detail the analyses in perspective books of complex bodies with systematically-delineated shadows. One book he undoubtedly knew is the sixteenth-century book on perspective by Daniele Barbaro, who illustrated virtuoso demonstrations of light and shade on geometrical bodies that were more complicated than the Platonic solids (Fig. 13). It was because Galileo was able to get a grip on what happens to mobile light and shade on a surface with projecting and sunken features, such as a human head, that he was able to throw the "picture" in his telescope into relief -- in a literal sense. Once you have seen it, of course, like other perceptions and illusions, you have "got it," and it subsequently becomes difficult to see it any other way.

In the nineteenth century exactly the same kind of skills were still needed when observers looked at the moon. Until men landed on the earth's planet, it remained necessary to understand what is being seen by using some kind of visual and physical analogies with phenomena to which we have earthly access. Astronomers had, in effect, to say: "That looks like something I have seen elsewhere." The earliest successful photographs of the moon illustrate this vividly, including those by Warren De La Rue and Joseph Beck, which were illustrated in 1874 in one of the finest of all the early photographically illustrated books, *The Moon: Considered as a Planet, a World and a Satellite*, by James Nasmyth and James Carpenter.

Looking at the rough surface of the moon, which was no longer a matter of doubt, the authors asked how we might understand the seen features in terms of the process that occurred during the formation of the moon (Fig. 15). The only way to propose an explanation is to formulate an essentially terrestrial analogy. They began to think about the behaviour of bodies that posses cores with skins. There were a number of available illustrations of what happens when the core of a body contracts or shrinks while its outer skin retains its predetermined surface area.

To let their readers understand their way of thinking, they produced photographic images that -- to use the cliché -- are worth more than a thousand words. James Nasmyth, incidentally, was the son of Alexander Nasmyth, who was the greatest Scottish landscape painter of his time. James, for his part, was a skilled draftsman and famed engineer, while James Carpenter was a major professional astronomer. They thought of ways of visualizing what happens with a body that contracts inside its skin. They illustrated a shrunken apple and an aged hand to make their point about the resultant wrinkling with extraordinary eloquence (Fig. 14).

Other of the structural intuitions witnessed in history are physical. They are not just seen but "felt." To operate this kind of intuition the visualizer needs to possess a kind of tactile empathy and intuition about the physicality of structure and process, about the manipulability of things, the stiffness of things, the elasticity of things, the fluidity of things, the general material properties of things, and the transformation of substances in space and time. We know, for instance, that Einstein worked a great deal with bodily intuitions, because the things he was dealing with were not seeable in the obvious way.

The most famed act of twentieth-century biological visualization also works very much in this visual-cum-physical way, namely the teasing out of the three-dimensional structure of DNA in 1953 by Watson and Crick. The problem they faced is that the available experimental data was registered as a flat superimposition of complex spatial episodes. The X-ray diffraction image they used, by Rosalind Franklin and Raymond Gosling, was based upon the deflections of X-rays through the 3-D structure of a hugely elaborate molecule. The process of image-formation is very similar to the way in which astronomers had designed astrolabes by projecting the celestial sphere onto the flat network of the rete, as a kind of map. From a fixed projection point the features are mapped onto the flat plane by a series of divergent lines. Essentially, what somebody modelling structure from an X-ray diffraction picture has to accomplish is the equivalent of deducing the three-dimensional structure of the planetary system from the rete of an astrolabe -- that is to say, envisaging three-dimensional from the flattened data. In fact, the problem faced with DNA is even more complicated. The geometry of the deflection is not as regular as the perspectival, straight-line projection in the astrolabe. Now if you said to somebody, “Reconstruct the 3-D form of the cosmos from that flat projection,” it would be a tough task and would require more information than is embedded in the image itself. But this is in essence what Watson and Crick did.

There were, to be sure, intermediate 3-D stages in the creation of their final model. One important type of model that became favoured in molecular biology in the 1950s and 1960s used sheets of translucent material, Lucite, to stack spatial slices of the density of the electrons as registered in the X-ray images. Scientists described how you could make visual sense of the Lucite models, which are far from simple to interpret. If you look at the electron density models, they appear disorderly from many directions. But the effect, as John Kendrew noted, is much like driving past a forest planted with trees in a regular grid. For much of the time, no patterns are readily discernible. Then, at a certain point as you are passing by, you suddenly see the perpendicular rows and you suddenly see the diagonals. Looking at a Lucite model is like that. You reach points of view from which things snap together and you see the underlying organization. Our minds are prepared and eagerly waiting for some kind of orderly structure to emerge. Movement, either of the object or of the observer, often plays a crucial role in making sense of complex arrays.

It was electron density maps that the great illustrator Irving Geis used as the primary source to create his extraordinary hand-made images of molecules. These precede, it is worth stressing, the computer graphics of molecules with which we are now so familiar. The aesthetics adopted in molecular modelling by computer was radically affected by the vision of Irving Geis. His complex, spatial images illustrating organic molecules in scientific papers and books are extraordinary acts of representation, and he was in his own right a designer/artist and illustrator of special genius.

Thus, when we look at the way in which Franklin and Gosling’s X-ray diffraction pictures were handled by Watson and Crick, we have to take into account the vigorous search for a variety of procedures that would permit the transformation of the flat to the 3-D, using various techniques of modelling and depiction. Even so, to move from the X-Ray diffraction image of DNA to its spatial configuration is at least as difficult an act of visualization as Kepler’s vision of the orbits of the planets as nested sequences of spheres and inscribed Platonic solids. Such acts of visualization are extraordinary acts of mental modelling.

The somewhat ramshackle model of DNA displayed by Watson and Crick in the famous photograph by Barrington Brown was dismembered as it was superseded by better models. The version now on display in the Science Museum in London is a pious reconstruction, which includes some of the original plates made by the Cambridge technicians and later recovered from America, where they had been taken by a member of the Cambridge laboratory. For an art historian, it is fascinating to see how this key historical artifact of science is composed of original bits and pieces with added modern elements, much like a Greek vase reconstructed from an incomplete set of shards. The Watson and Crick model, once an obsolete bit of scientific paraphernalia, is now being treated as a cultural treasure. In the museum it stands as a great cultural icon. The essay I wrote for the *Nature* publication celebrating the fiftieth year of DNA is called “The Mona Lisa of Modern Science.” The double helix is now a ubiquitous public image, exploited in all sorts of commercial wares, including jewellery and perfumes. Bijan markets a DNA perfume. Inevitably, the bottle assumes the form of the double helix.

The visualization of DNA occurred fifty years ago, and even the more recent conceiving of the structure of C^{60} belongs to history. What is happening now? We have already seen some contemporary practitioners at creative work, especially in architecture. I am certain that for scientists as for artists the kind of structural visualizations we have seen in action will continue to provide major resources for their discoveries and inventions. Let me conclude by looking at four recent episodes, one from cosmology, one from painting, and two from architecture. The architectural examples, as we will see, are much in the spirit of Fuller and Gaudí, though they superficially look like neither of them.

When I looked at the cover of *Nature* in October last year, I almost fell off my chair. There was a Keplerian, polyhedral model in elaborate glory, accompanied by the question "Is this the shape of the Universe?". The article inside, authored by the Parisian astronomer Jean-Pierre Luminet and his colleagues, posited that the recent data of microwave radiation could be best interpreted in terms of a dodecahdral model of the cosmos. It is, however, a model that exploits dimensions unknown to Kepler. The pentagonal faces are arranged around a sphere, and not an ordinary sphere at that, but rather a multi-dimensional hypersphere. The result is that a body can exit from one face and simultaneously enter from the opposite one. Although the mathematics lie far beyond those available to earlier devotees of the Platonic solids, Luminet himself acknowledges that his modes of visualisation are locked into a tradition that involves Leonardo and Albrecht Dürer, as well as his obvious scientific predecessors. It is satisfying to discover that he also practises as an artist and is deeply involved in music.

The painter I want to draw into this network of "geometrical structuralists" is Alex Colville, for me the most compelling Canadian painter from any period. Looking again at his work (after a gap of more than thirty years) and the growing body of literature on it, I was delighted but not surprised to see evidence of the way that he brings order from chaos -- one of his stated ambitions. Under the surface of his eerily super-real tableau, often deeply permeated by uneasy silences, lies a fretwork of geometrical configurations, existing both on the surface of the picture and in the perspectival construction of depth. Whereas perspectival armatures remain relatively overt in finished paintings, the surface harmonics make their shaping presence known through our own structural intuitions of the configurations that lie beneath the surface. The unstated emotional depths and the deep orders of formal structure are at one in Colville's art.

The first of the architectural examples is involved in a new but related form of mathematics. In 2002, a pavilion, a temporary summer shelter that served as a fresh-air café, was erected outside the Serpentine Gallery in Kensington Gardens in London. Its design was the fruit of intimate collaboration between the Japanese architect Toyo Ito and the London-based engineer Cecil Balmond of the Ove Arup partnership. The architect is traditionally seen as the "author" of the buildings he or she is commissioned to design, and the Serpentine pavilion certainly speaks of Ito's conceptually innovative approach. But Balmond, here as elsewhere in his work as an engineer collaborating with some of the world's most adventurous architects, does far more than just produce solutions to the obvious engineering problems. His input is vital at the conceptual and design levels. Balmond himself is an extraordinarily interesting figure, one who has succeeded in bringing his own background and interests in non-Western philosophies and Islamic geometry to bear on his creative thinking. He also has an enduring interest -- almost needless to say -- in D'Arcy Thompson. Here we see the architect searching within contemporary society for a radically new vocabulary of form, which Balmond is able to set into a wide, traditional context at the same time as operating at the cutting edge of engineering technologies.

The way Ito and Balmond designed the apparently chaotic patterns of triangular and rectilinear shapes in the roof and walls is that they began very simply by taking a basic square unit, which is successively turned by a third of a rotation. The process of iteration produces a fractal pattern of great visual variety. From an orderly process arises an extraordinary variety of related shapes. They then took this "fractal sheet" and wrapped it over a space defined as a half-cube. The structural properties of the underlying skeleton of the pattern was precisely what they needed to supplant the standard post-and-lintel construction of buildings over the ages. There are no structural posts at the corners. There are no beams running around or across the boundaries of the roof. There are no verticals supporting horizontals in the walls. The process of design has produced a new repertoire of architectural form and a new structural system. The structural intuitions at work in the Serpentine Pavilion are producing something very different in appearance from Fuller's domes and Gaudí's catenary arches, but I maintain that the underlying processes of insight well up from the same capacities of the mind in dialogue with the products of human invention and of nature.

The second case study relates particularly to the outcome of structural processes in nature. When Frank Gehry was struggling to bring sense into the apparently unresolvable variations of shape and technique in his never-ending (and never-constructed) project for the Lewis House, a breakthrough came when he exploited the extraordinarily complex curves adopted by a rumpled piece of felt -- an intuition closely related to his fascination with fold patterns of draperies in Old Master paintings. What the bulges, ridges, and hollows in the cloth suggested was that he could identify adjoining configurations that are as organically right as they are visually compelling.

These three episodes say very clearly that structural intuitions do not prescribe a certain kind of outcome. They correspond to a way of thinking, a way of visualizing, using lateral processes that are free to refer across a broad range of subject matter and source material, natural and man-made. It is clear that the potential of our ability to intuit diverse structures in art, science, and technology is effectively unlimited.

Is it possible to imagine future, as yet unused, potentialities in this way of thinking? Let me make, as a historian, one suggestion. Structure has been widely explored, process less so. Gehry is clearly involved in process, in the sense in which a dynamic process is used to arrive at a structural and aesthetic end. But I am thinking more of process in terms of the dynamism of the functioning of architectural spaces as containers for human flow. I am thinking of building a structure from the motions of users outwards towards space and structure -- a kind of architecture founded on fluid dynamics. Computers make this possible in a way that would have been impossible in the past. Perhaps someone is already doing this. If so, I would like to know.